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(71) Applicant: ROSEMOUNT INC. [US/US]; 12001 Technology Drive, Eden Prairie, MN 55344 (US).

(72) Inventor: WIKLUND, David, E.; 17918 South Shore Lane West, Eden Prairie, MN 55346 (US).

(74) Agents: KELLY, Joseph, R. et al.; Westman, Champlin & Kelly, International Centre - Suite 1600, 900 Second Avenue South, Minneapolis, MN 55402-3319 (US).

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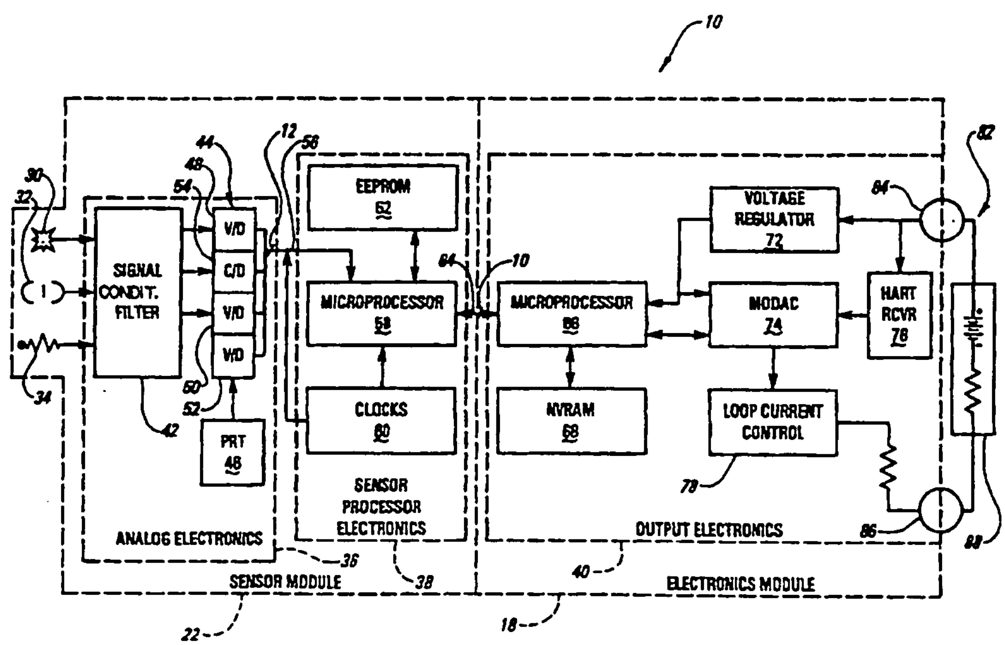

(57) Abstract

A transmitter (10) provides an output signal indicative of mass flow rate of fluid through a conduit (12). The transmitter (10) includes a temperature sensor (34) providing a temperature signal indicative of fluid temperature. A static pressure sensor (30) provides a static pressure signal indicative of static pressure in the conduit. A differential producer (32) provides a differential pressure signal. The transmitter (10) also includes a controller (66) which provides the output signal indicative of mass flow of the fluid through the conduit.

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TRANSMITTER FOR PROVIDING A SIGNAL INDICATIVE OF FLOW THROUGH A DIFFERENTIAL TRANSDUCER USING A SIMPLIFIED PROCESS

BACKGROUND OF THE INVENTION

The present invention deals with a transmitter in the process control industry. More particularly, the present invention deals with a simplified process, used in a transmitter, for providing an output signal indicative of flow through a differential producer.

Transmitters which sense various characteristics of fluid flowing through a conduit are known. Such transmitters typically sense and measure differential pressure, line pressure (or static pressure) and temperature of the process fluid. Such transmitters are typically mounted in the field of a refinery, or other process control industry installation. The field mounted transmitters are subject to significant constraints on power consumption. Such transmitters commonly provide an output in the form of a current representative of the variable being sensed. The magnitude of the current varies between 4-20 mA as a function of the sensed process variable. Therefore, the current available to operate the transmitter is less than 4 mA.

One way in which flow computation is done in industries such as the process control industry and the petroleum industry is through the use of dedicated flow computers. Such devices either use separate pressure, differential pressure and temperature transmitters or have sensing mechanisms housed in large enclosures. These devices are generally large and consume more power than 4 mA. Additionally, they are often limited to use in specialized applications such as the monitoring of

hydrocarbons for custody transfer or at wellheads to monitor the output of gas or oil wells.

Another way in which flow computation is done is through the use of local control systems, often called programmable loop controllers (PLC). PLC's typically receive inputs from separate pressure, differential pressure and temperature transmitters and compute the flow based on these inputs. Such devices are often performing additional local control tasks such as the calculation of other variables required in the control of the plant or the monitoring of process variables for alarm purposes. The calculation of flow in these devices requires programming by the user.

A third way in which flow computation is done is through the use of large computers which control entire plants, often called distributed control systems (DCS). DCS's typically perform a wide range of tasks ranging from receiving inputs from field-based transmitters to computing the intermediate process variables such as flow or level, to sending positioning signals to final control elements such as valves, to performing the monitoring and alarm functions within the plant. Because of the wide range of tasks required and the typically high cost of DCS input/output capability, memory and computational time, it is common to do a flow computation that is not compensated for all of the effects due to changing process conditions.

One common means of measuring flow rate in the process control industry is to measure the pressure drop across a fixed restriction in the pipe, often referred to as a differential producer or primary element. The general equation for calculating flow rate through a differential producer can be written as:

Equation 1

$$Q = N C_d E Y_1 d^2 \sqrt{\rho h}$$

where

Q = Mass flow rate (mass/unit time)

N = Units conversion factor (units vary)

C_d = Discharge coefficient (dimensionless)

E = Velocity of approach factor (dimensionless)

Y_1 = Gas expansion factor (dimensionless)

d = Bore of differential producer (length)

ρ = Fluid density (mass/unit volume)

h = Differential pressure (force/unit area)

Of the terms in this expression, only the units conversion factor, which is a constant, is simple to calculate. The other terms are expressed by equations that range from relatively simple to very complex. Some of the expressions contain many terms and require the raising of numbers to non-integer powers. This is a computationally intensive operation.

In addition, it is desirable to have the transmitter operate compatibly with as many types of differential producers as possible. Implementing all of the calculations and equations needed for the conventional flow equation in order to determine flow based on the output of one differential producer (much less a plurality of different types of differential producers) requires computations which can only be reasonably performed by a processor which has a high calculation speed and which is quite powerful. Operation of such a processor results in increased power consumption and memory requirements in the transmitter. This is highly undesirable given the 4 mA power

constraint or conventional transmitters. Therefore, current transmitter-based microprocessors, given the above power and memory constraints, simply do not have the capability of performing the calculations in any reasonable time period.

There has been some work done in obtaining a simplified discharge coefficient equation. However, this is only one small part of the flow equation. Even assuming the discharge coefficient is extremely simplified, implementing the flow equation accurately is still very difficult given the constraints on current transmitter-based microprocessors.

Other attempts have been made to simplify the entire flow equation. However, in order to make the flow equation simple enough that it can be implemented in transmitter-based microprocessors, the simplified flow equations are simply not very accurate. For example, some such simplified flow equations do not account for the discharge coefficient. Others do not account for compressibility, or viscosity effects.

Therefore, common transmitter-based microprocessors which are powered by the 4-20 mA loop simply do not accurately calculate flow. Rather, they provide outputs indicative of differential pressure across the orifice plate, static line pressure, and temperature. These variables are provided to a flow computer in a control room as mentioned above, which, in turn, calculates flow. This is a significant processing burden on the flow computer.

SUMMARY OF THE INVENTION

A transmitter provides an output signal indicative of mass flow rate of fluid through a conduit. The transmitter includes a temperature sensor providing a temperature signal indicative of fluid temperature.

A static pressure sensor provides a static pressure signal indicative of static pressure in the conduit. A differential producer provides a differential pressure signal. The transmitter also includes a controller which provides the output signal indicative of mass flow of the fluid through the conduit based on a plurality of simplified equations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a transmitter according to the present invention connected to a pipe which conducts fluid therethrough.

FIG. 2 is a block diagram, in partial schematic form of the transmitter according to the present invention.

FIGS. 3A-3C graphically illustrate curve fit accuracy for the discharge coefficient used by the system according to the present invention.

FIGS. 4A and 4B graphically illustrate curve fit accuracy of viscosity used according to the present invention.

FIG. 5 illustrates the curve fit accuracy of the term Ed^2 used according to the present invention.

FIG. 6 graphically illustrates the curve fit accuracy of the gas expansion factor used according to the present invention.

FIGS. 7A and 7B graphically illustrate the curve fit accuracy of fluid density for liquid used according to the present invention.

FIGS. 8A and 8B graphically illustrate curve fit accuracy of fluid density for gas used according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is an illustration of a transmitter 10 according to the present invention. Transmitter 10 is

coupled to a pipe 12 through pipe fitting or flange 14. Pipe 12 conducts flow of a fluid, either a gas or a liquid, in the direction indicated by arrow 16.

Transmitter 10 includes transmitter electronics module 18 and sensor module 22 which collectively house a transmitter more fully illustrated in FIG. 2. Transmitter electronics module 18 also preferably includes a boss 20 for accepting an input from a resistive temperature device (RTD), preferably a 100 ohm RTD which is typically inserted directly into the pipe or into a thermowell which is inserted into the pipe to measure the fluid temperature. The wires from the RTD are connected to one side of a terminal block in a temperature sensor housing 24. To the other side of the terminal block are connected wires which run through an electricl conduit 26 and are coupled to boss 20.

Sensor module 22 includes a differential pressure sensor and an absolute pressure sensor. The differential pressure sensor and absolute pressure sensor provide pressure signals to conditioning and digitizing circuitry, and to a linearizing and compensating circuit. The compensated, linearized and digitized signals are provided to the electronics module 18. The electronics module 18 in transmitter 10 provides an output signal indicative of process conditions of the process fluid flowing through pipe 12 to a remote location, by a 4-20 mA two-wire loop preferably formed using twisted pair conductors, through flexible conduit 28. In the preferred embodiment, transmitter 10 provides signals which are indicative of the three process variables (temperature, static pressure, and differential pressure) according to the HART® or Fieldbus Standards. Further, in accordance with the present invention, transmitter 10 also provides

an output signal indicative of flow. The method of determining flow according to the present invention is significantly simplified over prior methods allowing the microprocessor in the electronics module of transmitter 10 to calculate flow without exceeding the power constraints on the microprocessor, and at acceptably fast update times.

FIG. 2 is a more detailed block diagram of sensor module 22 and electronics module 18 of transmitter 10. Sensor module 22 includes a strain gauge pressure sensor 30, differential pressure sensor 32 and temperature sensor 34. Strain gauge sensor 30 senses the line pressure (or static pressure) of fluid flowing through conduit 12. Differential pressure sensor 32 is preferably formed as a metal cell capacitance-based differential pressure sensor which senses the differential pressure across an orifice in conduit 12. Temperature sensor 34, as discussed above, is preferably a 100 ohm RTD sensor which senses a process temperature of fluid in pipe 12. While, in FIG. 1, sensor 34 and sensor housing 24 are shown downstream of transmitter 10, this is but one preferred embodiment, and any suitable placement of temperature sensor 34 is contemplated.

Sensor module 22 also preferably includes an analog electronics portion 36, and a sensor processor electronics portion 38. Electronics module 18 includes output electronics portion 40. Analog electronics portion 36 in sensor module 22 includes signal conditioning and power supply filtering circuitry 42, analog-to-digital (A/D) circuitry 44, and PRT 46. The analog signals received from sensors 30, 32 and 34 are provided to analog signal conditioning and power supply filtering circuitry 42. The analog signals are

conditioned (such as amplified) and the conditioned analog signals are provided to A/D converter circuitry 44.

In a preferred embodiment, A/D converter circuitry 44 includes a plurality of voltage-to-digital converters, or capacitance-to-digital converters, or both (as appropriate) which digitize the analog input signals. Such converters are preferably constructed according to the teachings of U.S. Patent Nos. 4,878,012; 5,083,091; 5,119,033 and 5,155,455; assigned to the same assignee as the present invention. In the embodiment shown in FIG. 2, three voltage-to-digital converters 48, 50 and 52, and one capacitance-to-digital converter 54 are shown. The voltage-to-digital converters 48 and 50 are used to convert the signals from sensors 30 and 34 into digital signals. The capacitance-to-digital converter 54 is used to convert the signal from capacitive pressure sensor 32 to a digital signal.

PRT 46 is preferably formed as a low cost, silicon-based PRT positioned proximate pressure sensors 30 and 32. PRT 46 provides a temperature signal indicative of the temperature proximate sensors 30 and 32. This temperature signal is provided to voltage-to-digital converter 52 where it is digitized. This digitized signal is then used to compensate the differential and line pressure signals for temperature variations. Analog signal conditioning and power supply filtering circuitry 42, the A/D converters 44 and PRT 46 are all preferably physically located proximate to, or on, a single circuit board housed in transmitter 10.

Once the analog signals are digitized by A/D converters 44, the digitized signals are provided to sensor processor electronics portion 38 as four

respective sixteen bit wide outputs on any suitable connection or bus 56.

Sensor processor electronics portion 38 preferably includes a microprocessor 58, clock circuitry 60 and memory (preferably electrically erasable programmable read only memory, EEPROM) 62. Microprocessor 58 compensates and linearizes the process variables received from analog electronics portion 36 for various sources of errors and non-linearity. For instance, during manufacture of transmitter 10, pressure sensors 30 and 32 are individually characterized over temperature and pressure ranges, and appropriate correction constants are determined. These correction constants are stored in EEPROM 62. During operation of transmitter 10, the constants in EEPROM 62 are retrieved by microprocessor 58 and are used by microprocessor 58 in calculating polynomials which are, in turn, used to compensate the digitized differential pressure and static pressure signals.

Clock circuitry 60 is provided in sensor processor electronics portion 38 and provides clock signals to microprocessor 58, A/D circuits 44 and to other electronics as appropriate, in order to accomplish the desired operations. It should also be noted that the functionality of portions 36 and 38 can be combined into a single integrated circuit chip through application specific integrated circuit (ASIC) technology.

After the analog signals from sensors 30, 32 and 34 are digitized, compensated and corrected, the process variable signals are provided over a serial peripheral interface (SPI) bus 64 to output electronics portion 40 in electronics module 18. SPI bus 64 preferably includes power signals, two hand shaking

signals and the three signals necessary for typical SPI signaling.

Output electronics module 40 preferably includes microprocessor 66, non-volatile memory 68, voltage regulator 72, modulator circuit 74, HART® protocol receiver 76 and loop current controller 78. In addition, output electronics portion 40 may optionally be coupled to a battery back-up circuit which provides battery power to the output electronics in case of failure of the power provided over the two-wire loop.

Microprocessor 66 receives the digitized, compensated process variables over SPI bus 64. In response, and as will be described in greater detail later in this specification, microprocessor 66 calculates the mass flow of fluid flowing through pipe 12 based on the process variables received over bus 64. This information is stored in non-volatile memory 68 which, preferably, is suitable for storing up to 35 days worth of mass flow data.

When requested, microprocessor 66 configures output electronics 40 to provide the mass flow data stored in non-volatile memory 68 over two-wire loop 82. Therefore, output electronics 40 is coupled at positive and negative terminals 84 and 86 to loop 82 which includes controller 88 (modeled as a power supply and a resistor). In the preferred embodiment, output electronics 40 communicates over two-wire loop 82 according to a HART® communications protocol, wherein controller 88 is configured as a master and transmitter 10 is configured as a slave. Other communications protocols common to the process control industry may be used, with appropriate modifications to the code used with microprocessor 66 and to the encoding circuitry. Communication using the HART® protocol is accomplished

by utilizing HART® receiver 76. HART® receiver 76 extracts digital signals received over loop 82 from controller 88 and provides the digital signals to circuit 74 which, in turn, demodulates the signals according to the HART® protocol and provides them to microprocessor 66.

Circuit 74 receives digital signals (which are to be sent over loop 82) from microprocessor 66. Circuit 74 converts the digital signals into analog signals, modulates them for transmission, and provides the modulated signals to circuit 76. Circuit 74 preferably includes a Bell 22 compatible modem. The loop current control circuit 78 receives an analog voltage signal from a D/A converter in circuit 74. In response, loop current control circuit 78 provides a 4-20 mA output representative of the particular information being transmitted by microprocessor 66 over loop 82 (such as one of the process variables, or the calculated flow).

Also, voltage regulator 72 preferably provides 3.5 volts and other suitable reference voltages to output electronics circuity 40, sensor processor electronics 38, and analog electronics 36.

In order to calculate flow through a differential producer (such as an orifice plate) information is required about three things. Information is required about the process conditions, about the geometry of the differential producer and about the physical properties of the fluid. Information about the process conditions is obtained from sensor signals, such as the signals from sensors 30, 32 and 34. Information regarding the geometry of the differential producer and the physical properties of the fluid are provided by the user.

Flow through a differential producer is conventionally calculated by utilizing the equation set out as Equation 1 above. Flow is typically calculated in mass units, but can be expressed in volumetric units if required. The choice of units determines the value of the units conversion factor, N.

The discharge coefficient, C_d, is a dimensionless, empirical factor which corrects theoretical flow for the influence of the velocity profile of the fluid in the pipe, the assumption of zero energy loss in the pipe, and the location of pressure taps. C_d is related to the geometry of the differential producer and can be expressed as a seemingly simple relationship in the following form:

Equation 2

$$C_d = C_\infty + \frac{b}{Re_D^n}$$

where the Reynolds number

$$Re_D^n = \frac{KQ}{\mu D};$$

C_∞ = the discharge coefficient at infinite Reynolds number;

b = a known Reynolds number correction term;

n = a known exponent term; and

μ = the fluid viscosity.

This relationship varies for different types of differential producers, the location of the pressure taps on such producers, and the beta ratio. Typical equations defining C_d and the other above terms have a wide range of complexity and are set out in Table 1. The calculation for C_d associated with an orifice plate-

type differential producer is the most common in the industry.

The velocity of approach factor, E, is a geometrical term and relates the fluid velocity in the throat of the differential producer to that in the remainder of the pipe. The velocity of approach factor is a function of temperature as follows:

Equation 3

$$E = \frac{1}{\sqrt{1-\beta^4}}$$

where, for an orifice meter,

Equation 4

$$\beta = \frac{d_r[1+\alpha_1(T-T_r)]}{D_r[1+\alpha_2(T-T_r)]}$$

d_r = orifice diameter at reference temperature T_r;

D_r = meter tube diameter at reference temperature T_r;

α_1 = thermal expansion coefficient of the orifice plate; and

α_2 = thermal expansion coefficient of a meter tube.

The gas expansion factor Y_1 is a dimensionless factor which is related to geometry, the physical properties of the fluid and the process conditions. The gas expansion factor accounts for density changes as the fluid passes through a differential producer. The gas expansion factor for primary elements with abrupt changes in diameter, such as orifice meters, is given by the following empirical relationship:

Equation 5

$$Y_1 = 1 - (.41 + .35\beta^4)\frac{h}{27.73PK}$$

where h = differential pressure in inches of water at 68°F;

P = upstream pressure in psia; and

K = isentropic exponent of the gas.

The adiabatic gas expansion factor for contoured elements is described as follows:

Equation 6

$$Y_1 = \left[\frac{(1-\beta^4)\,[K/K-1)]\,(P_2/P_1)^{2/K}[1-(P_2/P_1)^{(K-1/K)}]}{[1-\beta^4(P_2/P_1)^{(2/K)}]\,(1-P_2/P_1)}\right]^{1/2}$$

where

Equation 7

$$\frac{P_2}{P_1} = 1 - \frac{h}{27.73P}$$

K = isentropic exponent of the gas.

The value of Y_1 is 1.0 for liquids.

The bore of the differential producer, d, is related to geometry and is a function of temperature as follows:

Equation 8

$$d = d_r[1 + \alpha_1(T - T_r)]$$

The differential pressure factor, h, is measured by a conventional differential pressure sensor.

The fluid density factor ρ is described in mass per unit volume and is a physical property of the fluid. For typical process control applications, the

density of liquids is a function of temperature only. It can be described by expressions such as the PTB equation for the density of water:

Equation 9

$$\rho = A + BT + CT^2 + DT^3 + ET^4 + FT^5$$

where A-F are constants, or a generic expression given by the American Institute of Chemical Engineers (AIChE):

Equation 10

$$\rho = \frac{aM}{b^{1+(1-T/C)^d}}$$

Where a-d are fluid dependent constants and M is the molecular weight.

Gas density is a function of absolute pressure and absolute temperature given by the real gas law:

Equation 11

$$\rho = \frac{P}{nZR_oT}$$

where Z = the compressibility factor;
R_o = universal gas constant; and
n = number of moles.

Gas density and compressibility factors are calculated using equations of state. Some equations of state, such as AGA8, the ASME steam equation and MBWR, are useful for single fluids or a restricted number of fluids. Others, such as Redlich-Kwong or AIChE equations of state are generic in nature and can be used for a large number of fluids. The AIChE equation is as follows:

Equation 12

$$\rho = M\left[-\frac{1}{2B}-\frac{1}{2}\left[\frac{1}{B^2}\ \frac{4P}{BRT}\right]^{1/2}\right]$$

where

Equation 13

$$B = a + \frac{b}{T} + \frac{c}{T^3} + \frac{d}{T^8} + \frac{e}{T^9}$$

where a-e are fluid dependent constants; and

M = the molecular weight of the fluid.

Implementing the flow calculation using equations 1-13 set out above would yield a highly accurate result. However, the constraints of power consumption, calculation speed and memory requirements make the implementation of the full equations beyond the capability of currently available transmitter based microprocessors. Therefore, the transmitter of the present invention calculates flow based on a number of simplified equations, while retaining a high degree of accuracy in the flow calculation.

The dependencies related to the discharge coefficient are as follows:

C_d (β, Re_D);

Re_D (Q, μ) where μ is the viscosity of the fluid; and

μ (T)

Using the AIChE equation for liquids:

Equation 14

$$\mu = \exp\left(a + b/T + c\,Ln(T) + d\,T^e\right);$$

and, using AIChE equation for gases:

Equation 15

$$\mu = \frac{aT^b}{1 + c/T + d/T^2}$$

According to the present invention, the discharge coefficient C_d equation is simplified by approximating μ^{-1} by a polynomial in T or 1/T. Preferably, this approximation is done using a third degree polynomial equation. Also, C_d is approximated using a sixth degree polynomial equation in

$$\frac{1}{\sqrt{Re_D}}$$

or

$$\frac{1}{Ln(Re_D)}$$

It has been observed that better accuracy is obtained using the polynomial for C_d with the term

$$\frac{1}{Ln(Re_D)}$$

being the independent variable, but this also increases the calculation time. Therefore, this can be used, or the other polynomial can be used, depending upon the degree of accuracy desired.

FIGS. 3A, 3B and 3C are examples of curve fit accuracy of the discharge coefficient using the above equations. FIG. 3A is a graph of the discharge coefficient curve fit error versus the Reynolds number for an ASME flange tap orifice meter having a diameter

in excess of 2.3 inches. This graph was obtained by doing a sixth degree fit in

$$\frac{1}{\sqrt{Re_D}}$$

as follows:

Equation 16

$$C_d = b_0 + \frac{1}{\sqrt{Re_D}}\left(b_1 + \frac{1}{\sqrt{Re_D}}\left(b_2 + \frac{1}{\sqrt{Re_D}}\left(b_3 + \frac{1}{\sqrt{Re_D}}\left(b_4 + \frac{1}{\sqrt{Re_D}}\left(b_5 + \frac{b_6}{\sqrt{Re_D}}\right)\right)\right)\right)\right)$$

and using an approximation of viscosity as follows:

Equation 17

$$\mu^{-1} = a_0 + \frac{1}{T}\left(a_1 + \frac{1}{T}\left(a_2 + a_3\frac{1}{T}\right)\right)$$

FIG. 3B graphically illustrates the discharge coefficient curve fit error plotted against Reynolds number for an ASME corner tap orifice meter using a sixth degree fit in

$$\frac{1}{\sqrt{Re_D}}$$

FIG. 3C graphically illustrates the discharge coefficient curve fit error against Reynolds number for an ASME long radius nozzle using the sixth degree fit in

$$\frac{1}{\sqrt{Re_D}}$$

FIGS. 3A-3C illustrate that the curve fit approach approximates the discharge coefficient C_d to better than +/-0.005%. Similar results are obtained for other differential producers.

FIGS. 4A and 4B are examples of curve fit accuracy obtained for viscosity. FIG. 4A graphically illustrates curve fit accuracy for viscosity versus temperature using a third degree polynomial fit in 1/T. FIG. 4B illustrates the curve fit accuracy for viscosity versus temperature using a third degree polynomial fit in 1/T. FIG. 4A is based on water and FIG. 4B is calculated for air. It is seen that the curve fit approach approximates the viscosity of air to better than +/- 0.001% and the viscosity of water to better than +/- 0.2%. A polynomial fit of a higher degree in 1/T, such as 4 or 5, would improve the accuracy of the fit for water. Because the discharge coefficient, C_d, is weakly dependent on Reynolds number and, thus, viscosity, the accuracy provided using a third degree polynomial fit in 1/T is acceptable and the added computational complexity of a higher degree polynomial approximation is not necessary. Similar results are obtained for other liquids and gases.

The dependencies related to the velocity of approach factor, E, and the bore of the differential producer, d, are as follows:

$$E(T), \text{ and } d^2(T).$$

The method of the present invention simplifies the Ed^2 calculation by grouping E and d^2 together and approximating the product of Ed^2 by a polynomial in T or 1/T. This polynomial is preferably a second degree polynomial.

FIG. 5 is an example of the curve fit accuracy of the Ed^2 term. FIG. 5 graphically illustrates the accuracy of this term plotted against temperature using a second degree polynomial in T as follows:

Equation 18

$$Ed^2 = c_0 \frac{1}{T}\left(c_1 + \frac{1}{T}c_2\right)$$

FIG. 5 illustrates that the curve fit approach approximates the Ed^2 term to better than +/-0.00002%.

The dependencies of the gas expansion factor, Y_1, are as follows:

$$Y_1(\beta, K, \frac{h}{P})\ ;\ and$$

$$Y_1(T)$$

Simplifying the gas expansion factor calculation is accomplished by ignoring the dependency on T. The Y_1 term is approximated using a polynomial equation in h/P where h is the differential pressure and P is the static pressure. Preferably, this polynomial is a second degree polynomial. For an orifice, a linear relationship exists between Y_1 and h/P.

FIG. 6 is an example of curve fit accuracy of Y_1 versus temperature using a second degree polynomial fit in h/P as follows:

Equation 19

$$Y_1 = d_0 + \frac{h}{P}\left(d_1 + \frac{h}{P}d_2\right)$$

The curve is illustrated for a contoured element differential producer. FIG. 6 illustrates that

the term Y_1 for contoured elements is accurate, using the system according to the present invention, to better than +/-0.002% for all beta ratios. Accuracy is better than +/-0.0005% for beta ratios less than 0.6. Similar results are obtained for the square edged orifice.

Dependencies related to the fluid density for liquid and gas are as follows:

$$\rho_{Liq}(T)\ ;\ and$$

$$\rho_{Gas}(P,T)\ ,\ specifically\ \rho_{Gas} = \left(\frac{P}{RT}\right)\frac{1}{Z}$$

The fluid density calculation for liquid is simplified according to the present invention by providing two levels of curve fit. The term $\sqrt{\rho_{liq}}$ is approximated by a polynomial in T or 1/T. Preferably, this is a third degree polynomial and is provided as a default equation for a lower accuracy fit as follows:

Equation 20

$$\sqrt{\rho} = e_0 + \frac{1}{T}\left(e_1 + \frac{1}{T}\left(e_2 + \frac{1}{T}e_3\right)\right)$$

The same term is also preferably approximated by a polynomial in 1/T using a fifth degree polynomial as a higher accuracy fit for broader operating ranges of temperature.

Simplifying the calculation for fluid density for gas is accomplished by, again providing two levels of curve fit. Fitting a curve to $\frac{1}{\sqrt{Z}}$ and not ρ_{Gas} improves the curve fit accuracy, reduces calculation time, and improves the simplified flow equation accuracy. According to the present invention, the term $\frac{1}{\sqrt{Z}}$ is approximated by a polynomial in P and 1/T. In the

preferred embodiment, the default polynomial is a 3X2 polynomial and is used for a lower accuracy fit. However, the term $\frac{1}{\sqrt{z}}$ can also be approximated by a polynomial in P and 1/T using an 8X6 polynomial for higher accuracy fits, and for broader operating ranges of both P and T. The preferred simplified equation for fluid density for all gases is as follows:

Equation 21

$$\sqrt{\rho} = \left[\frac{144M_w}{R}\right]^{.5}\left[\frac{P}{T}\right]^{.5}\Big[f_0 + P(f_1 + P(f_2 + pf_3)) + \frac{1}{T}\Big((f_4 + P(f_5 + P(f_6 + Pf_7))) + \frac{1}{T}(f_8 + P(f_9 + P(f_{10} + Pf_{11})))\Big)\Big]$$

FIG. 7A graphically illustrates an example of curve fit accuracy for $\sqrt{\rho_{liq}}$ for water versus temperature using the third degree polynomial fit in 1/T. FIG. 7B graphically illustrates curve fit accuracy density of acrylonitrile versus temperature. In both cases, the temperature range is 50°F to 110°F. FIGS. 7A and 7B illustrate that the curve fit approach approximates $\sqrt{\rho_{liq}}$ to better than +/-0.0002% for these two liquids and the selected temperature range. Similar results are obtained for other liquids and other temperature ranges.

FIGS. 8A and 8B illustrate examples of curve fit accuracy for $\frac{1}{\sqrt{z}}$ for two fluids and pressure temperature ranges. FIG. 8A illustrates the curve fit accuracy using the 3X2 polynomial fit for carbon dioxide gas. The pressure and temperature ranges are 15 psia to 115 psia and 60°F to 140°F. The results show that the curve fit approach accurately approximates $\frac{1}{\sqrt{z}}$ to better than +/- 0.0015%. FIG. 8B illustrates the curve

fit accuracy using the 3X2 polynomial fit for ethylene gas. The pressure and temperature ranges are 75 psia to 265 psia and 60°F to 140°F. The results show that the curve fit approach accurately approximates $\frac{1}{\sqrt{z}}$ to better then +/- 0.005%. As these results indicate, the accuracy of the curve fit approximation varies, as the fluid is changed and as the operating ranges of pressure and/or temperature change. When the operating ranges of pressure and/or temperature result in unacceptable approximations by using a 3X2 polynomial, an 8X6 polynomial will improve the results to levels similar to those indicated in FIGS. 8A and 8B.

In sum, the classic flow calculation given by Equation 1 above, is simplified according to the present invention as follows:

Equation 22

$$Q = N\,[C_d]\,[Ed^2]\,[Y_1]\,[\sqrt{\rho}]\,\sqrt{h}$$

For gases this equation can be rewritten as:

$$Q = KN\ [C_d]\,[Ed^2]\,[Y_1]\left[\frac{1}{\sqrt{z}}\right]\sqrt{\frac{hP}{T}}$$

where

$$K = \sqrt{\frac{144M}{R}}$$

M = molecular weight of the gas;

R = gas constant; and

P, h, T are in units of psia, inches of water and degrees Rankine, respectively. For liquids, the equation can be rewritten as:

$$Q = N\ [C_d]\,[Ed^2]\,[Y_1]\,[\sqrt{\rho}]\,\sqrt{h}$$

where the bracketed terms are curve fit approximations. By simplifying the flow equation as set out above, the transmitter based microprocessor 66 is capable of updating the flow calculation each time it receives updated sensor information by bus 64. In the event that one or more of the curve fit approximations have not been completely calculated the previous value is used in the flow calculation.

The effect of variations in the process variables has a direct affect on the flow calculation by virtue of their appearance in the flow equation. They have a smaller effect on the curve fit terms. Thus, by using the newly updated process variable information and the most recently calculated curve fit approximations, the result is a flow calculation that is both fast and accurate. Having newly calculated flow terms at such an expedient update rate allows transmitter 10 to exploit fast digital communication protocols.

Also, by simplifying the flow calculation as set out above, microprocessor 66 performs the same calculations regardless of the type of differential producer used, regardless of the beta ratio used, and regardless of whether the user requires a simplified or fully compensated flow.

It should also be noted that the curve fit coefficients are easily calculable by the user using known techniques. These coefficients are simply stored in memory associated with microprocessor 66 and used in performing the desired calculations.

These simplifications allow transmitter 10 to actually calculate flow in a highly accurate manner. Rather than requiring the transmitter to simply transmit the process variables back to a control room, and have a flow computer in the control room or installation

calculate flow, the transmitter according to the present invention is capable of not only providing the process variables, but also providing a flow calculation to the control room. This relieves the processing overhead on the flow computer or other processor in the control room, yet does not over burden the transmitter-based microprocessor, or require the transmitter-based microprocessor to use energy which exceeds that available to it.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A transmitter for providing an output signal indicative of mass flow rate of fluid through a conduit, the transmitter comprising:

a temperature sensor providing a temperature signal indicative of fluid temperature;

a static pressure sensor providing a static pressure signal indicative of static pressure in the conduit;

a differential producer providing a differential pressure signal; and

a microcomputing circuit, coupled to the temperature sensor, the static pressure sensor, and the differential producer, to receive the temperature signal, the static pressure signal and the differential pressure signal, and providing an output signal indicative of flow of the fluid through the conduit based on a plurality of polynomial equations using polynomial curve fits with at least one of temperature, static pressure and differential pressure being an independent variable in each of the polynomial equations.

2. The transmitter of claim 1 wherein the microcomputing circuit includes:

a first microprocessor coupled to the temperature sensor, static pressure sensor and differential producer, and corrects the static pressure signal, differential producer signal and temperature signal for non-linearities

and provides corrected output signals; and

a second microprocessor, coupled to the first microprocessor, for calculating flow based on the corrected output signals.

3. A 4-20 mA process control transmitter coupled to a conduit conducting a fluid therethrough, the transmitter comprising:

a first pressure sensor sensing line pressure in the conduit and providing a line pressure signal indicative of the line pressure;

a second pressure sensor sensing differential pressure across an orifice in the conduit and providing a differential pressure signal indicative of the differential pressure;

a temperature sensor sensing temperature of the fluid and providing a temperature signal indicative of the temperature of the fluid; and

a microcomputing circuit, coupled to the first and second pressure sensors and the temperature sensor and powered by a 4-20 mA loop, calculating flow of the fluid through the conduit based on the line pressure signal, the differential pressure signal and the temperature signal and providing an output signal indicative of the flow.

4. The transmitter of claim 3 wherein the controller is configured to calculate flow based on at least one polynomial equation using a polynomial curve fit with at least one of temperature, static pressure

and differential pressure being an independent variable in the polynomial equation.

5. The transmitter of claim 4 wherein the controller calculates flow, Q, according to an equation generally of the form:

$$Q = N\,[C_d]\,[Ed^2]\,[Y_1]\,[\sqrt{\rho}]\,\sqrt{h}$$

wherein N is a units conversion factor, C_d is a discharge coefficient, E is a velocity of approach factor, d is a bore diameter of the second pressure sensor, Y_1 is a gas expansion factor, ρ is fluid density at operating temperature and pressure, and h is the differential pressure, and wherein at least one of C_d, E, d^2, y_1, and ρ are approximated by the polynomial equation curve fit.

6. The transmitter of claim 5 wherein the controller calculates flow based on a plurality of polynomial equations using polynomial curve fits to approximate a plurality of C_d, E, d^2, Y_1, and ρ with at least one of the temperature, the static pressure and the differential pressure being an independent variable in the polynomial equations.

7. The transmitter of claim 5 wherein the controller calculates flow based on an approximation of C_d according to a polynomial equation having the form:

$$C_d = \sum_{i=o}^{n} \left(\frac{1}{\sqrt{Re_D}}\right)^i b_i$$

8. The transmitter of claim 7 wherein C_d is calculated as:

$$C_d = b_0 + \frac{1}{\sqrt{Re_D}}\left(b_1 + \frac{1}{\sqrt{Re_D}}\left(b_2 + \frac{1}{\sqrt{Re_D}}\left(b_3 + \frac{1}{\sqrt{Re_D}}\left(b_4 + \frac{1}{\sqrt{Re_D}}\left(b_5 + \frac{b_6}{\sqrt{Re_D}}\right)\right)\right)\right)\right)$$

9. The transmitter of claim 5 wherein the controller calculates flow based on an approximation of Ed^2 according to a polynomial equation having the form:

$$Ed^2 = \sum_{i=0}^{n} C_i \left(\frac{1}{T}\right)^i$$

10. The transmitter of claim 9 where Ed^2 is calculated as:

$$Ed^2 = c_0 + \frac{1}{T}\left(c_1 + \frac{1}{T}c_2\right)$$

11. The transmitter of claim 5 wherein the controller calculates flow based on an approximation of Y_1 according to a polynomial equation having the form:

$$Y_1 = \sum_{i=0}^{n} \left(\frac{h}{P}\right)^i d_i$$

12. The transmitter of claim 11 wherein Y_1 is calculated as:

$$Y_1 = d_0 + \frac{h}{P}\left(d_1 + \frac{h}{P}d_2\right)$$

13. The transmitter of claim 5 wherein the controller calculates flow based on an approximation of

ρ for liquid according to a polynomial equation having the form:

$$\sqrt{\rho} = \sum_{i=0}^{n} \left(\frac{1}{T}\right)^{i} e_i$$

14. The transmitter of claim 13 wherein ρ for liquid is calculated as:

$$\sqrt{\rho} = e_0 + \frac{1}{T}\left(e_1 + \frac{1}{T}\left(e_2 + e_3 \frac{1}{T}\right)\right)$$

15. The transmitter of claim 5 wherein ρ for a gas is calculated as:

$$\sqrt{\rho} = \left[\frac{144 M_w}{R}\right]^{.5} \left[\frac{P}{T}\right]^{.5} \sum_{i=0}^{n} \sum_{j=0}^{m} P^{i} \left(\frac{1}{T}\right)^{j} f_{ij}$$

16. The transmitter of claim 15 wherein ρ for gas is calculated as:

$$\sqrt{\rho} = \left[\frac{144 M_w}{R}\right]^{.5} \left[\frac{P}{T}\right]^{.5} \Big[f_{00} + P(f_{10} + P(f_{20} + f_{30}P)) + \frac{1}{T}\Big((f_{01} + P(f_{11} + P(f_{21} + f_{31}P))) + \frac{1}{T}(f_{02} + P(f_{12} + P(f_{22} + f_{32}P)))\Big)\Big]$$

17. The transmitter of claim 5 wherein C_d is calculated using an equation generally in the form:

$$C_d = \sum_{i=0}^{n} \left(\frac{1}{\ln(Re_D)}\right)^{i} b_i$$

18. The transmitter of claim 16 wherein C_d is calculated as:

$$C_d = b_o + \frac{1}{\ln(Re_d)}\left(b_1 + \frac{1}{\ln(Re_D)}\left(b_2 + \frac{1}{\ln(Re_D)}\right.\right.$$

$$\left.\left.\left(b_3 + \frac{1}{(Re_D)}\left(b_4 + \frac{1}{\ln(Re_D)}\left(b_5 + \frac{b_6}{\ln(Re_D)}\right)\right)\right)\right)\right)$$

19. The transmitter of claim 5 wherein the term Ed^2Y_1 is calculated using an equation in the form:

$$Ed^2Y_1 = a_o + \frac{1}{T}\left(a_1 + \frac{a_2}{T}\right)$$

$$+ \frac{h}{P}\left[a_3 + \frac{1}{T}(a_4 + \frac{a_5}{T}) + \frac{h}{P}(a_6 + \frac{1}{T}(a_7 + \frac{a_3}{T}))\right]$$

20. A method of providing an indication of flow of fluid through a conduit using a process control transmitter powered by a 4-20mA control loop, comprising:

sensing static pressure and providing a static pressure signal indicative of the static pressure;

sensing differential pressure and providing a differential pressure signal indicative of the differential pressure;

sensing temperature and providing a temperature signal indicative of the temperature; and

calculating flow of the fluid through the conduit based on the static pressure signal, the differential pressure signal and the temperature signal and providing an output signal indicative of the flow.

Fig. 1

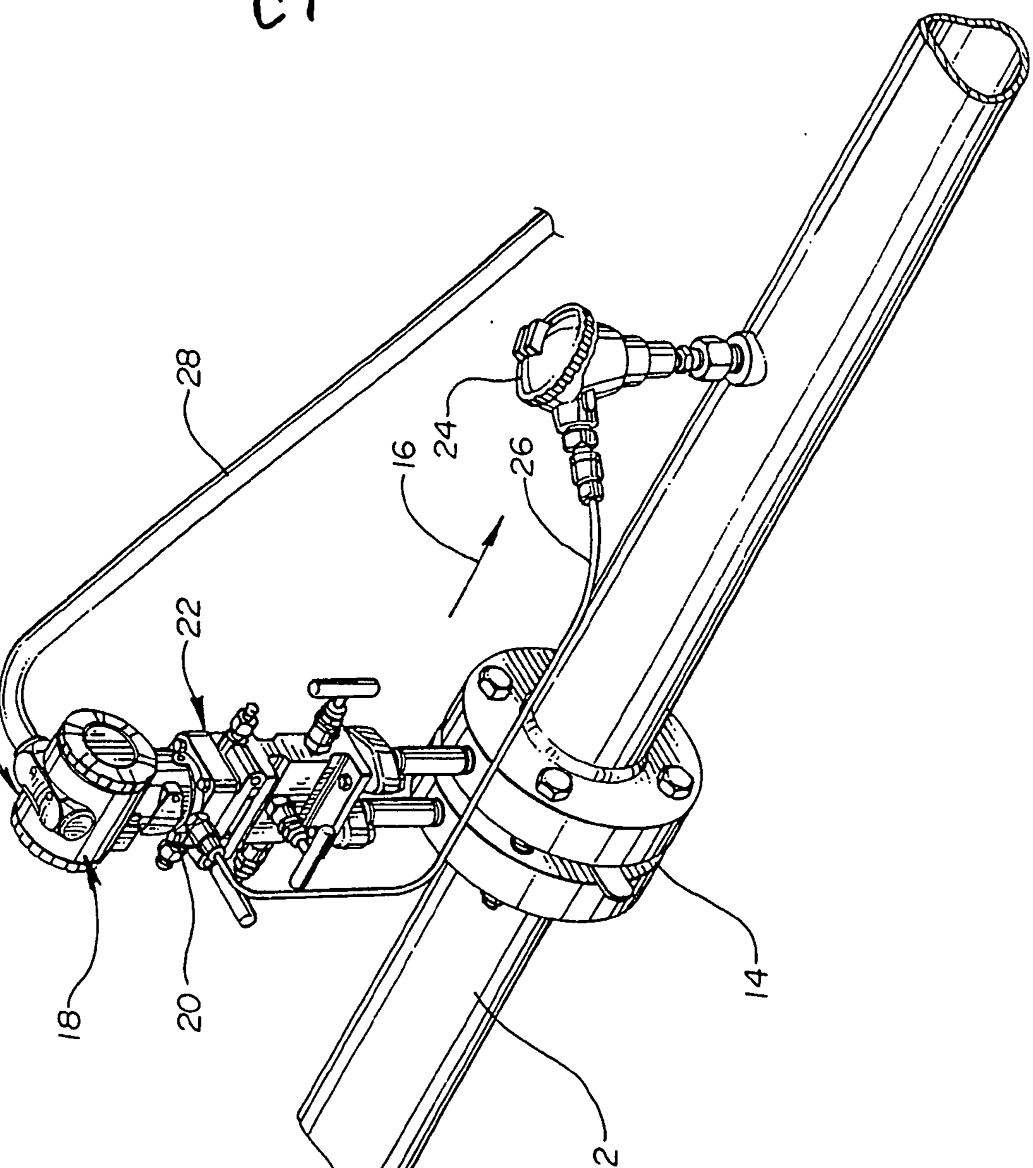


Fig. 2

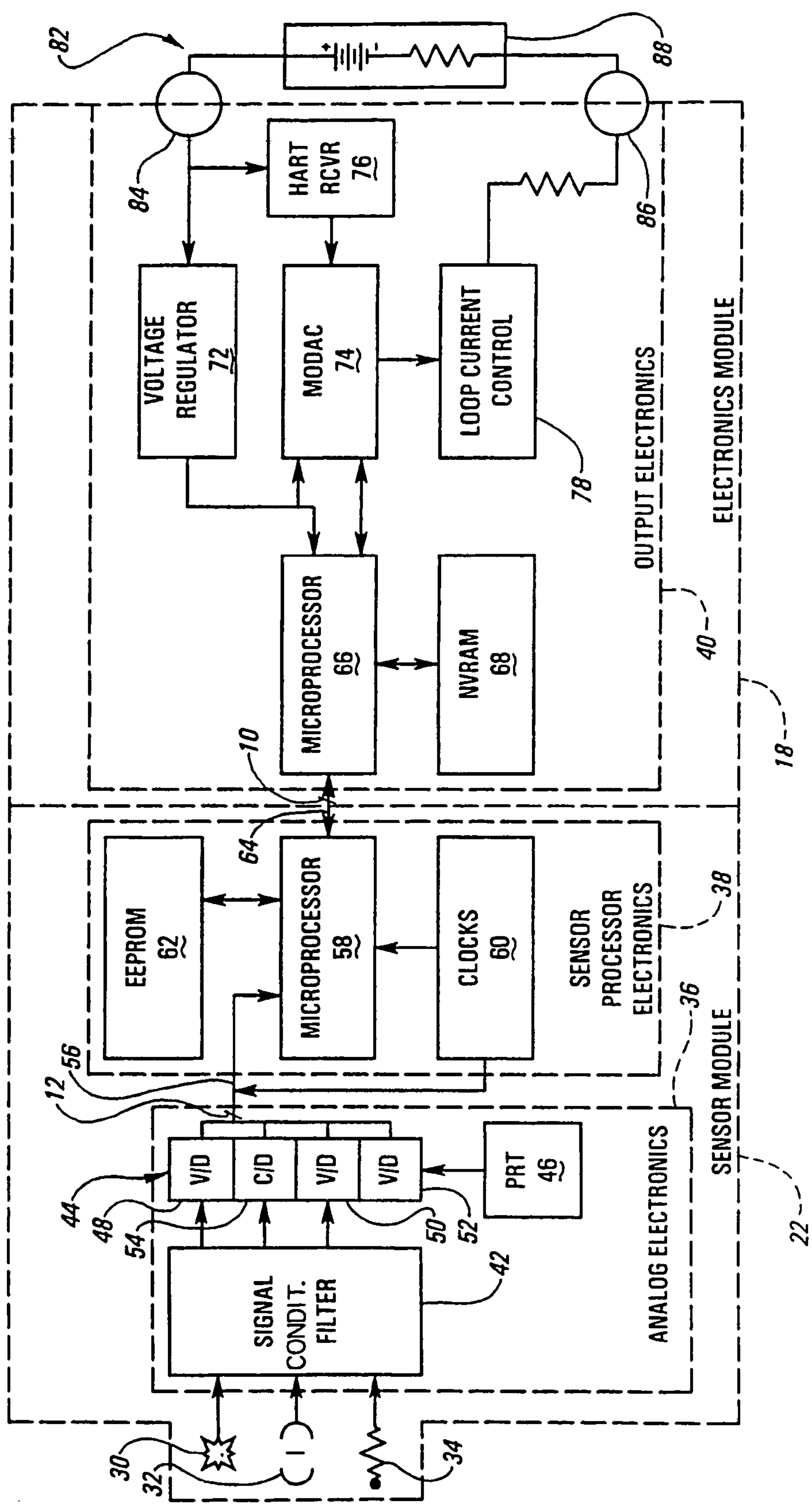
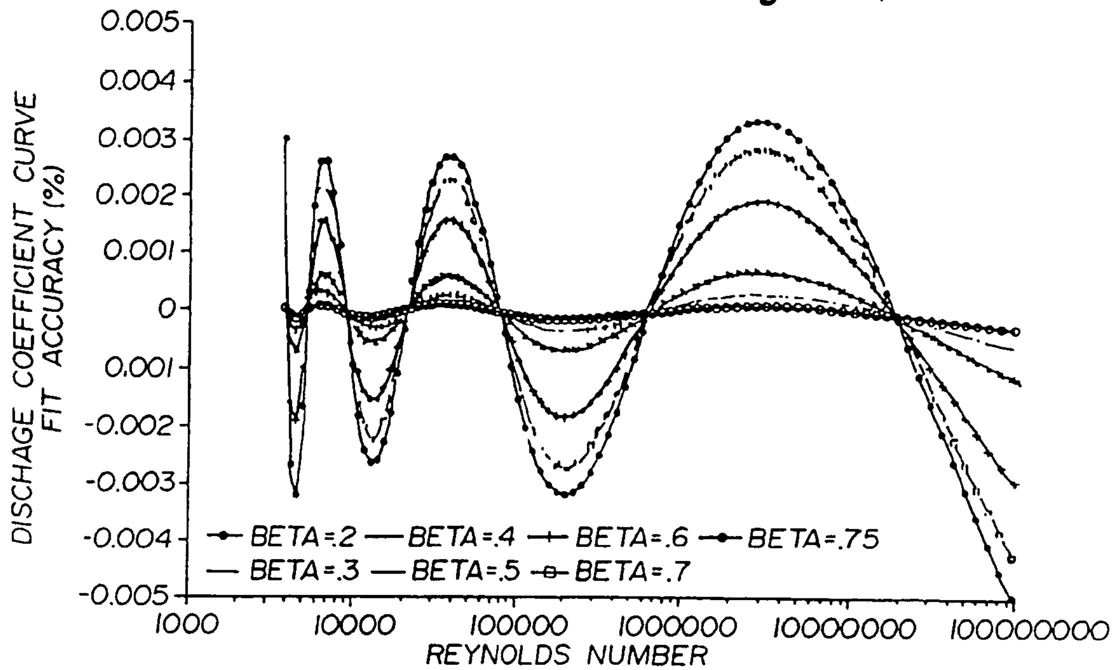
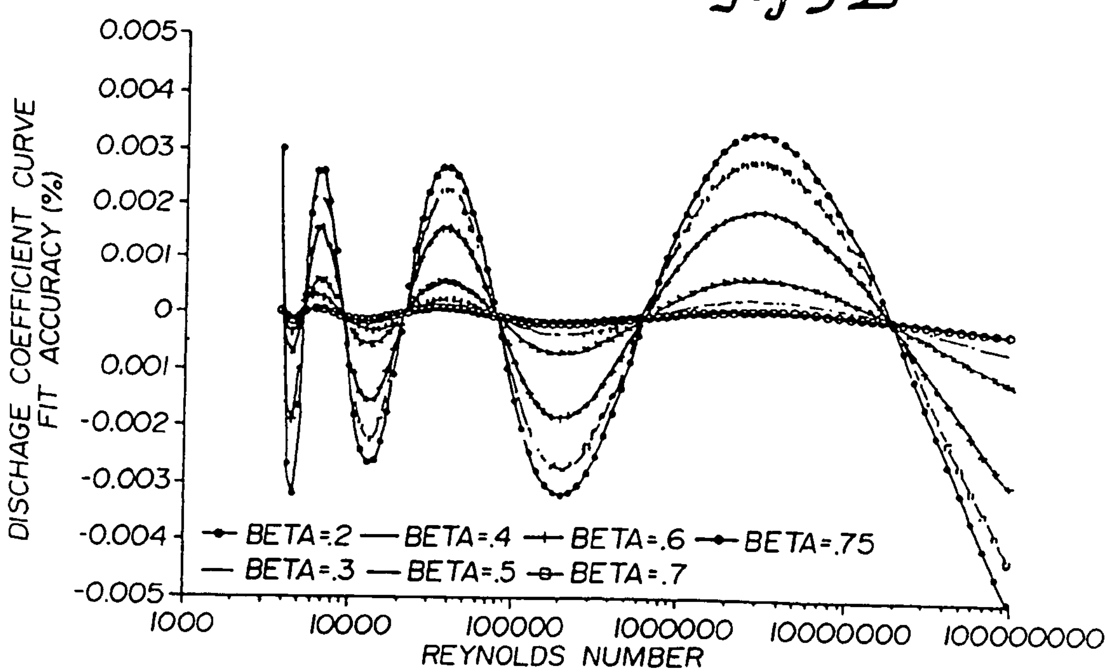

HART RCVR 76
VOLTAGE REGULATOR 72
MODAC 74
LOOP CURRENT CONTROL
MICROPROCESSOR 66
NVRAM 68
OUTPUT ELECTRONICS
ELECTRONICS MODULE
EEPROM 62
MICROPROCESSOR 58
CLOCKS 60
SENSOR PROCESSOR ELECTRONICS
V/D
C/D
V/D
V/D
PRT 46
SIGNAL CONDIT. FILTER
ANALOG ELECTRONICS
SENSOR MODULE
82
84
86
88
78
40
18
10
64
38
36
56
12
44
48
54
50
52
42
22
30
32
34

Fig.3A



0.005
0.004
0.003
0.002
0.001
0
0.001
-0.002
-0.003
-0.004
-0.005
DISCHAGE COEFFICIENT CURVE
FIT ACCURACY (%)
BETA=.2
BETA=.4
BETA=.6
BETA=.75
BETA=.3
BETA=.5
BETA=.7
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER

Fig.3B



0.005
0.004
0.003
0.002
0.001
0
0.001
-0.002
-0.003
-0.004
-0.005
DISCHAGE COEFFICIENT CURVE
FIT ACCURACY (%)
BETA=.2
BETA=.4
BETA=.6
BETA=.75
BETA=.3
BETA=.5
BETA=.7
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER

Fig.3C

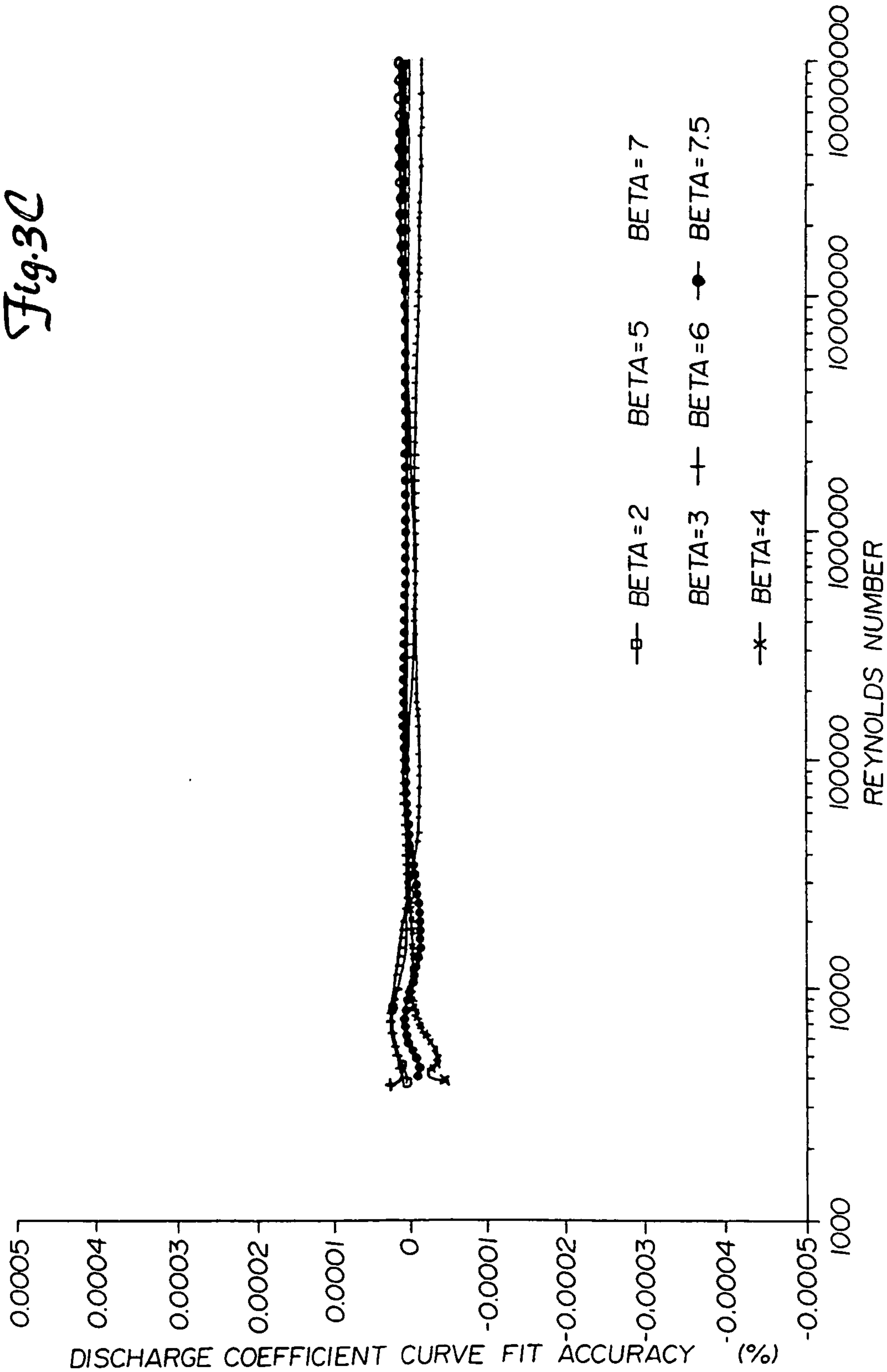

DISCHARGE COEFFICIENT CURVE FIT ACCURACY (%)
0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER
BETA=2
BETA=3
BETA=4
BETA=5
BETA=6
BETA=7
BETA=7.5

Fig. 4A

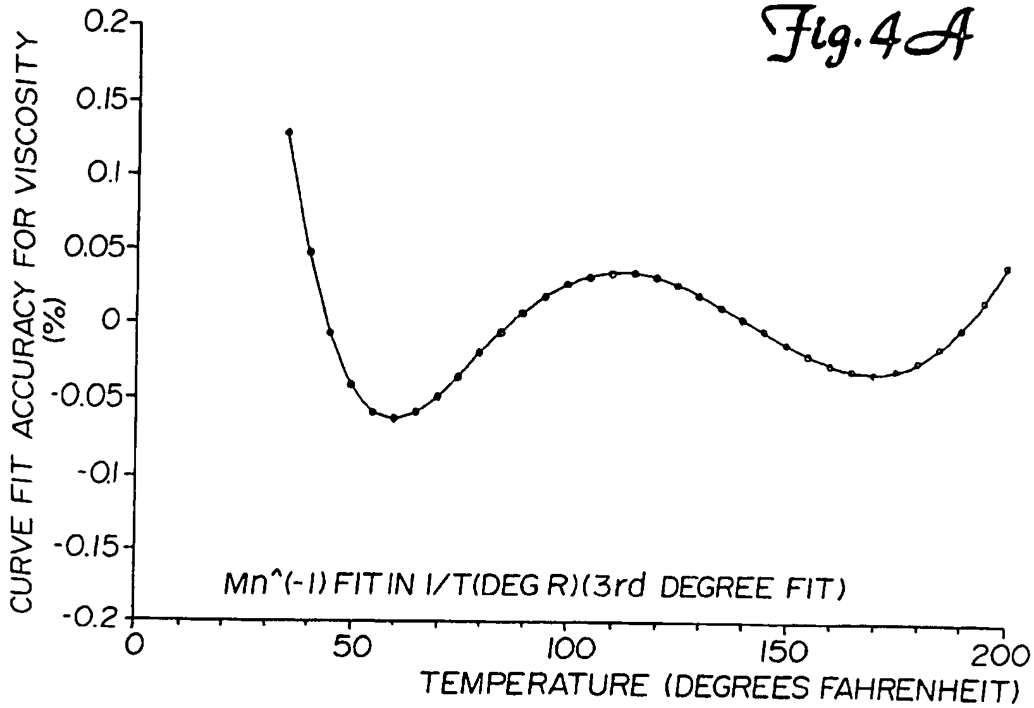
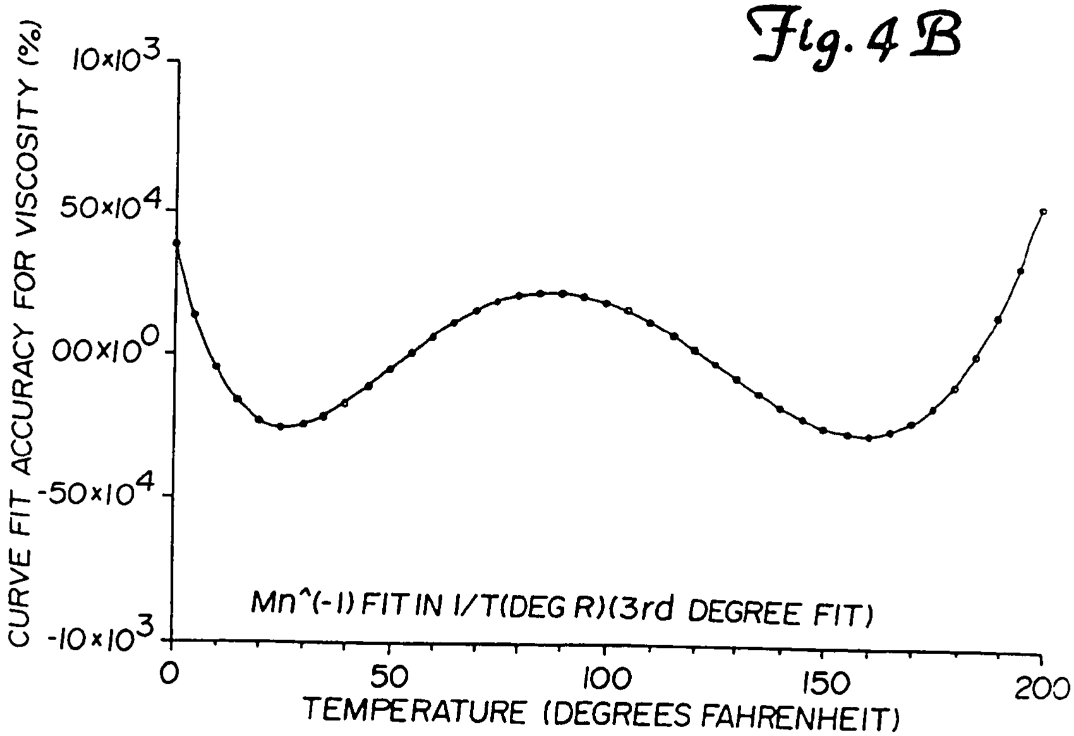

CURVE FIT ACCURACY FOR VISCOSITY (%)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Mn^(-1) FIT IN 1/T(DEG R)(3rd DEGREE FIT)
0
50
100
150
200
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 4B


CURVE FIT ACCURACY FOR VISCOSITY (%)
10x10³
50x10⁴
00x10⁰
-50x10⁴
-10x10³
Mn^(-1) FIT IN 1/T(DEG R)(3rd DEGREE FIT)
0
50
100
150
200
TEMPERATURE (DEGREES FAHRENHEIT)

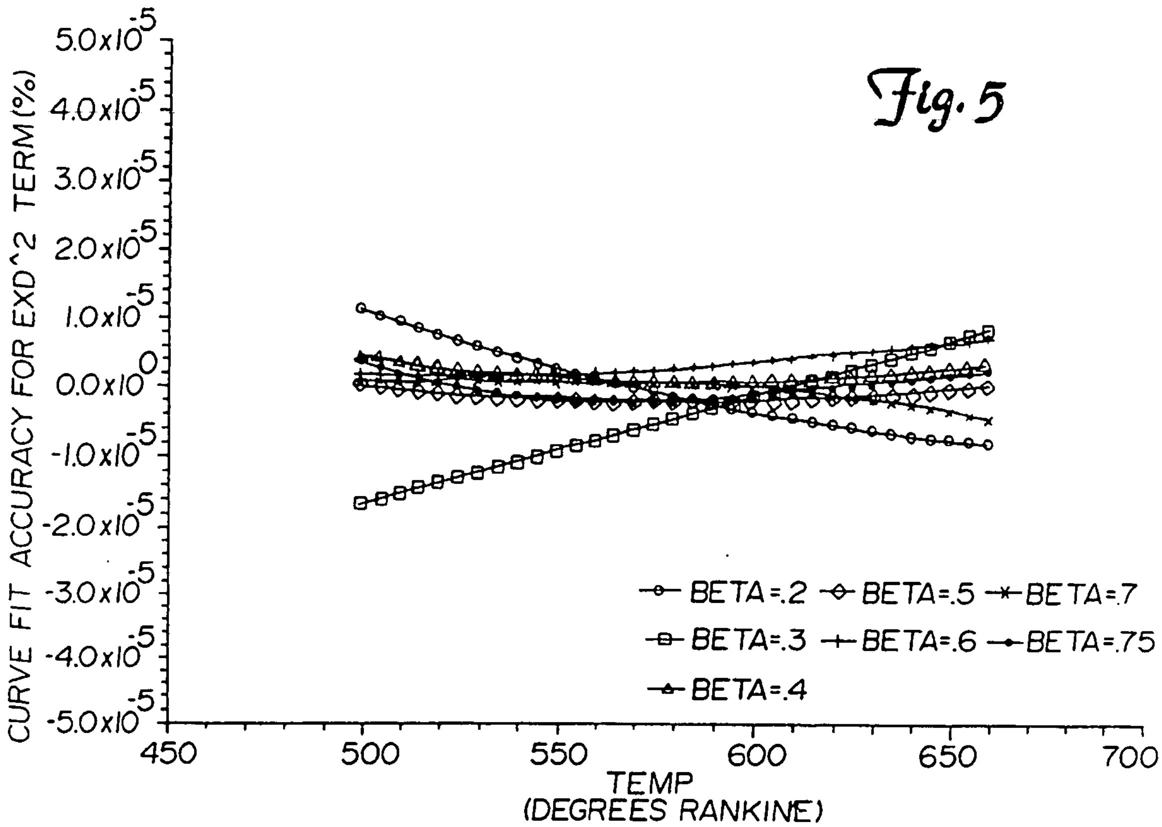
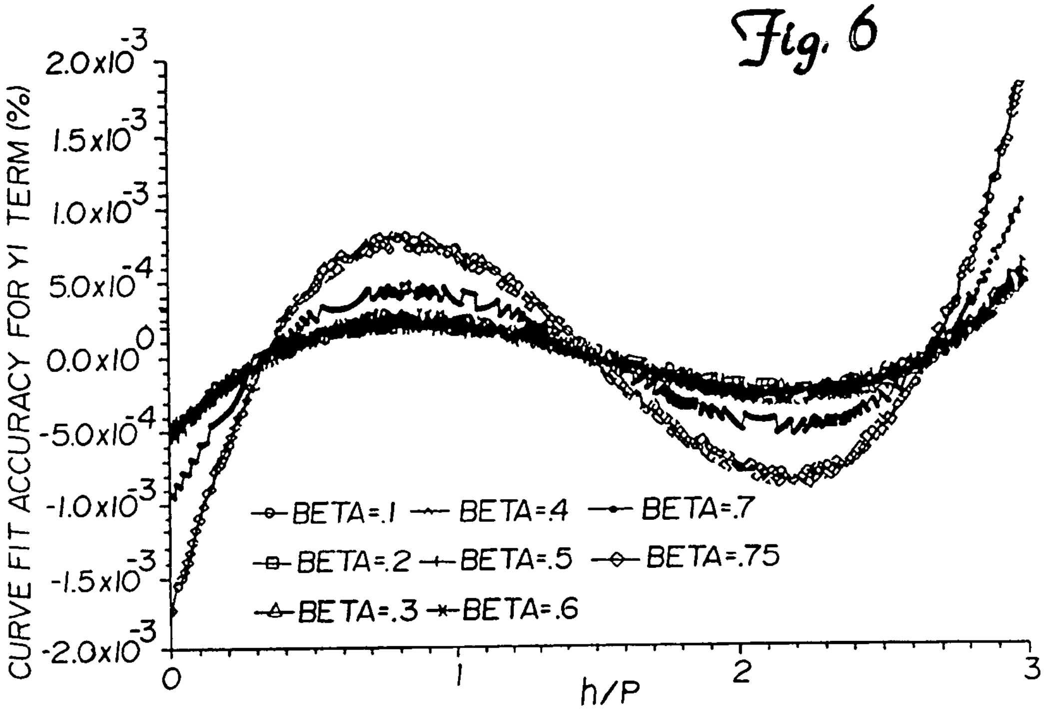

CURVE FIT ACCURACY FOR EXD^2 TERM(%)
5.0x10^-5
4.0x10^-5
3.0x10^-5
2.0x10^-5
1.0x10^-5
0.0x10^0
-1.0x10^-5
-2.0x10^-5
-3.0x10^-5
-4.0x10^-5
-5.0x10^-5
450
500
550
600
650
700
TEMP
(DEGREES RANKINE)
BETA=.2
BETA=.5
BETA=.7
BETA=.3
BETA=.6
BETA=.75
BETA=.4

Fig. 5

Fig. 6


2.0x10^{-3}
1.5x10^{-3}
1.0x10^{-3}
5.0x10^{-4}
0.0x10^{0}
-5.0x10^{-4}
-1.0x10^{-3}
-1.5x10^{-3}
-2.0x10^{-3}
CURVE FIT ACCURACY FOR YI TERM (%)
0
1
2
3
h/P
BETA=.1
BETA=4
BETA=.7
BETA=.2
BETA=.5
BETA=.75
BETA=.3
BETA=.6

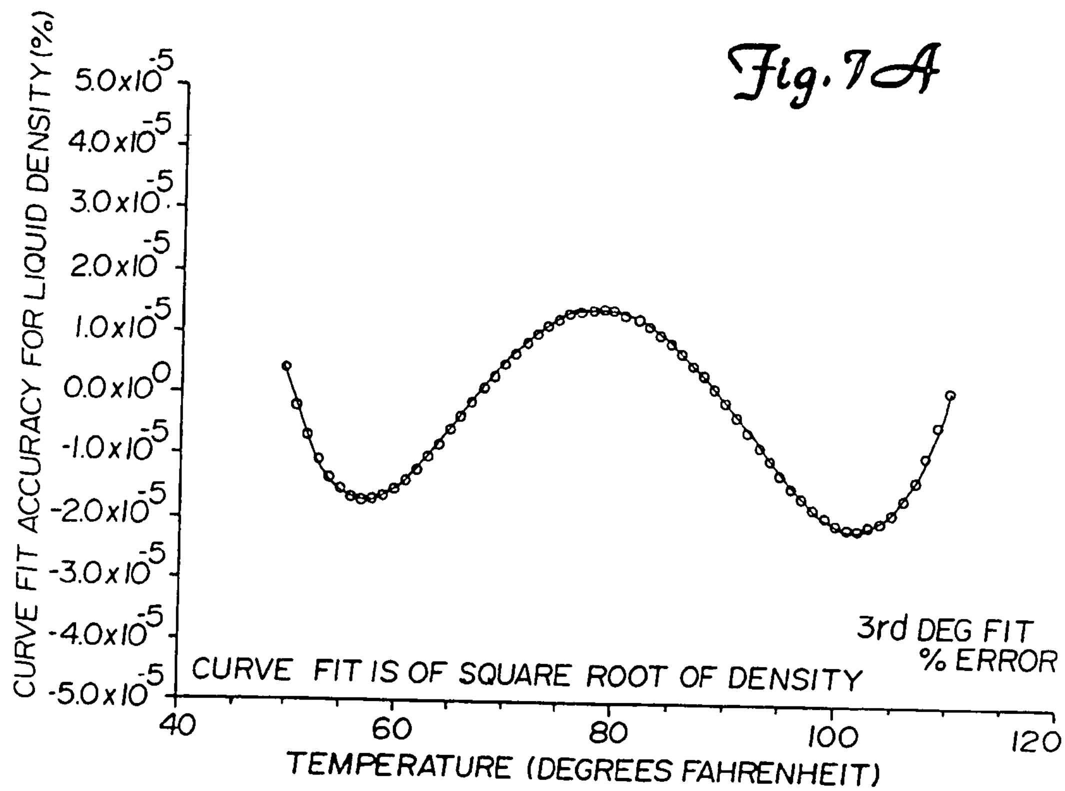

CURVE FIT ACCURACY FOR LIQUID DENSITY (%)
5.0x10^-5
4.0x10^-5
3.0x10^-5
2.0x10^-5
1.0x10^-5
0.0x10^0
-1.0x10^-5
-2.0x10^-5
-3.0x10^-5
-4.0x10^-5
-5.0x10^-5
3rd DEG FIT
% ERROR
CURVE FIT IS OF SQUARE ROOT OF DENSITY
40
60
80
100
120
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 7A

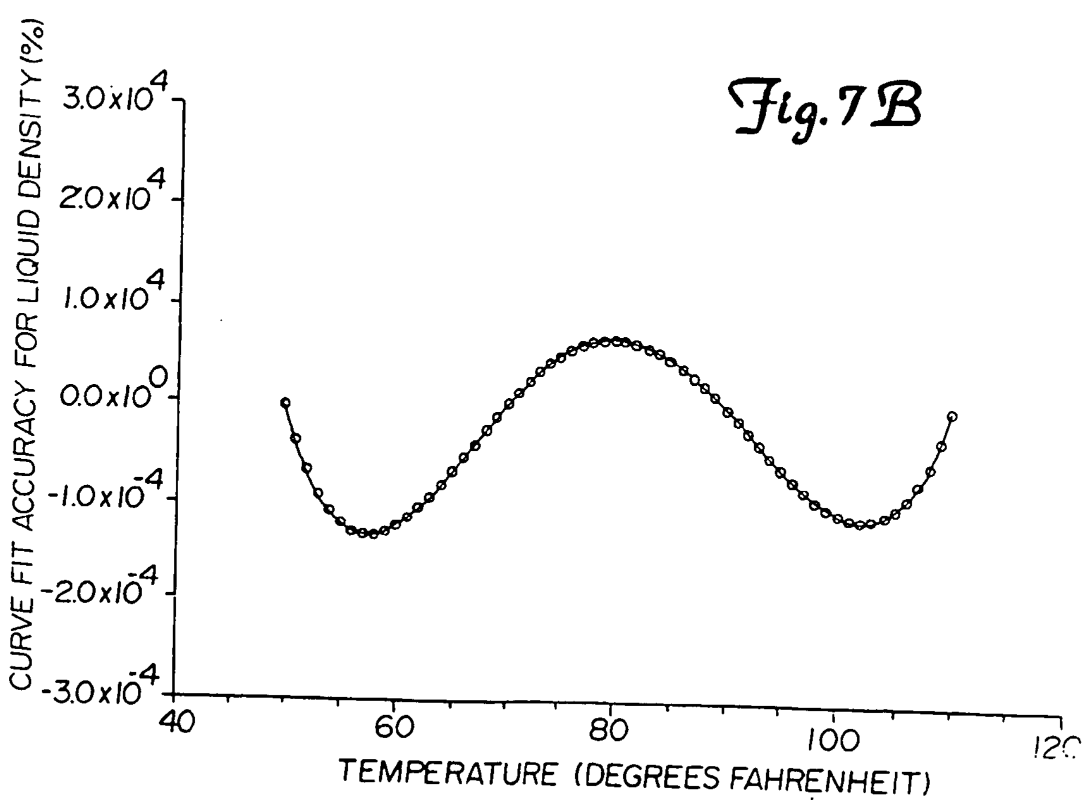

CURVE FIT ACCURACY FOR LIQUID DENSITY (%)
3.0x10^4
2.0x10^4
1.0x10^4
0.0x10^0
-1.0x10^-4
-2.0x10^-4
-3.0x10^-4
40
60
80
100
120
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 7B

Fig. 8A

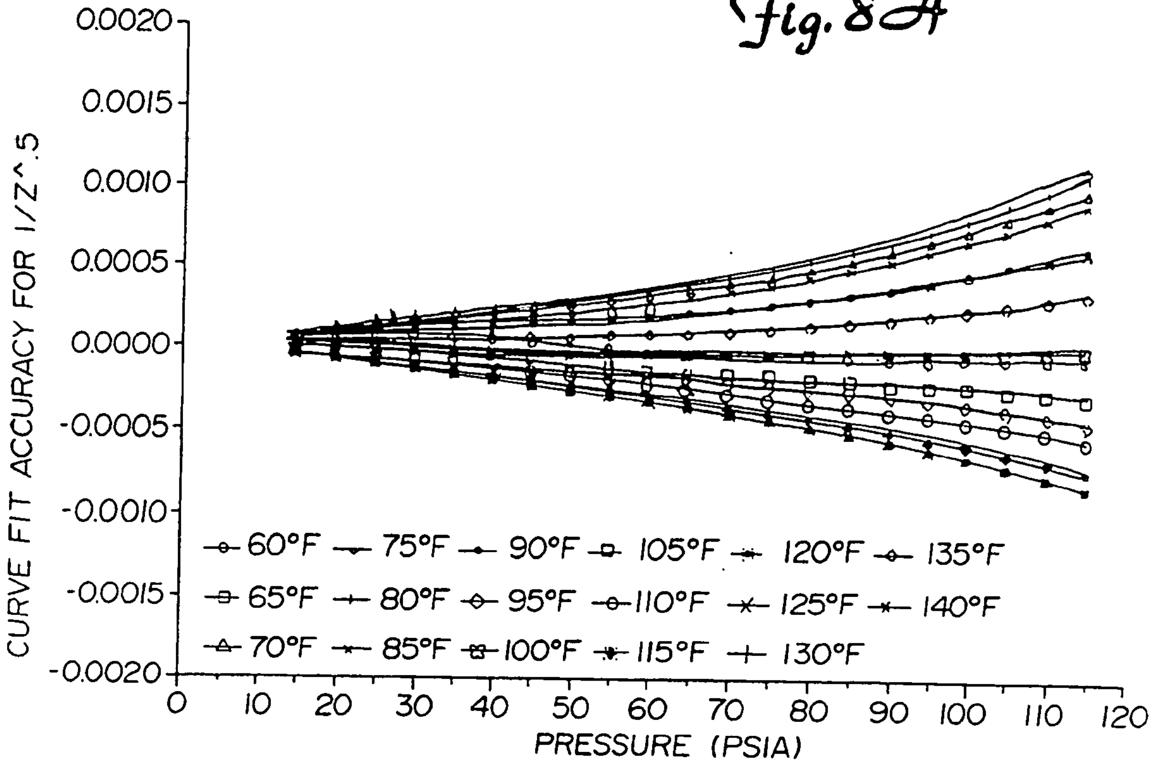

CURVE FIT ACCURACY FOR 1/Z^.5
PRESSURE (PSIA)
60°F 75°F 90°F 105°F 120°F 135°F
65°F 80°F 95°F 110°F 125°F 140°F
70°F 85°F 100°F 115°F 130°F

Fig. 8B

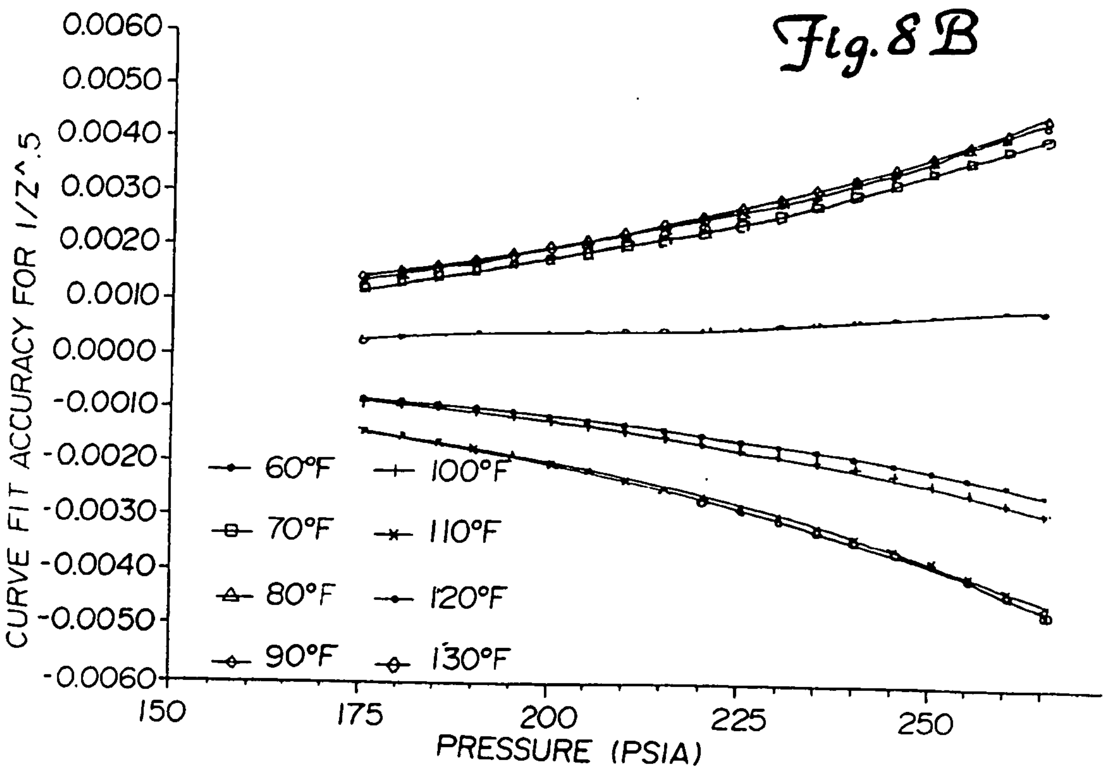

CURVE FIT ACCURACY FOR 1/Z^.5
PRESSURE (PSIA)
60°F 100°F
70°F 110°F
80°F 120°F
90°F 130°F

TABLE 1

DISCHARGE COEFFICIENT EQUATIONS FOR COMMON DIFFERENTIAL PRODUCER

DIFFERENTIAL PRODUCER	C_∞	b	n
VENTURI: MACHINED INLET	.995	0	0
VENTURI: ROUGH CAST INLET	.984	0	0
VENTURI: ROUGH WELDED SHEET-IRON INLET	.985	0	0
NOZZLE: ASME LONG RADIUS	.9975	$-6.53\ \beta^{0.5}$	0.5
NOZZLE: ISA	$.9900 - 0.2262\ \beta^{4.1}$	$(-0.00175\ \beta^{2} + .0033\ \beta^{4.15})10^{6.9}$	1.15
ASME ORIFICE: CORNER TAPS	$.5959 + .0312\ \beta^{2.1} - .184\ \beta^{8}$	$91.71\ \beta^{2.5}$	0.75
ASME ORIFICE: FLANGE TAPS $(D > 2.3)$	$.5959 + .0312\ \beta^{2.1} - .184\ \beta^{8} + .09\ \frac{\beta^{4}}{D(1-\beta^{4})} - .0337\ \frac{\beta^{3}}{D}$	$91.71\ \beta^{2.5}$	0.75
ASME ORIFICE: FLANGE TAPS $(2 \leq D \leq 2.3)$	$.5959 + .0312\ \beta^{2.1} - .184\beta^{8} + .039\ \frac{\beta^{4}}{1-\beta^{4}} - .0337\ \frac{\beta^{3}}{D}$	$91.71\ \beta^{2.5}$	0.75
ASME ORIFICE: D & D/2 TAPS	$.5959 + .0312\ \beta^{2.1} - .184\ \beta^{8} + .039\ \frac{\beta^{4}}{1-\beta^{4}} - .0158\ \ \beta^{3}$	$91.71\ \beta^{2.5}$	0.75
AGA ORIFICE: FLANGE TAPS (NOTE: FORMAT IS DIFFERENT FROM THAT OF OTHER EQUATIONS)	$C_d(FT) = C_i(FT) + 0.000511\left[\frac{10^{6}\ \beta}{Re_D}\right]^{0.7} + (0.021 + 0.0049\ A)\ \beta^{4}C$ $C_i(FT) = C_i(CT) + \text{TAP TERM}$ $C_i(CT) = 0.5961 + .00291\beta^{2}\ - 0.220\ \beta^{8}\ + 0.003(1-\beta)M_1$ $\text{TAP TERM} = \text{UPSTRM} + \text{DNSTRM}$ $\text{UPSTRM} = [0.0433 + 0.0712e^{-8.5/D}\ - 0.1145e^{-6.0/D}\ ](1-0.23\ A)B$ $\text{DNSTRM} = -0.0116[M_2 - 0.52\ M_2^{1.3}]\beta^{1.1}\ (1-0.14\ A)$ $B = \frac{\beta^{4}}{1-\beta^{4}}$ $M_1 = \text{MAX}(2.8-D,0.0)$ $M_2 = \frac{2}{D(1-\beta)}$ $A = \left[\frac{19000\beta}{Re_D}\right]^{0.8}$ $C = \left[\frac{10^{6}}{Re_D}\right]^{0.35}$		

Fig. 9

INTERNATIONAL SEARCH REPORT

Inte   onal Application No
PCT/US 96/11515

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01F1/50

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,4 562 744 (HALL KENNETH R ET AL) 7 January 1986 see column 2, line 28 - column 6, line 19; figure 1 ---	1
A	US,A,4 249 164 (TIVY VINCENT V) 3 February 1981 see column 4, line 24 - column 5, line 46; figure 11 ---	1-20
A	US,A,4 799 169 (MIMS CHARLES R) 17 January 1989 see column 4, line 4 - column 5, line 46; figure 1 --- -/--	1-20

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

1

Date of the actual completion of the international search	Date of mailing of the international search report
28 October 1996	18. 11. 96
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl, Fax (+ 31-70) 340-3016	Authorized officer Heinsius, R

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Int. onal Application No
PCT/US 96/11515

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,4 796 651 (GINN LEROY D ET AL) 10 January 1989 see column 4, line 14 - column 5, line 43; figure 1 ---	1-20
X	ADVANCES IN INSTRUMENTATION, vol. 31, no. 4, April 1976, pages 847-1-847-4, XP002016947 R.D. GOODENOUGH: "DIGITAL COMPUTERS FOR GAS MEASURING SYSTEMS" see figure 2 ---	20
A	CONTROL AND INSTRUMENTATION, vol. 8, no. 8, September 1976, pages 28-29, XP002016948 "SIGNAL TRANSMISSION PUT ON A PEDESTAL" see page 28, left-hand column, paragraph 4; figure 1 -----	3,20

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Information on patent family members

International Application No
PCT/US 96/11515

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